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A SIX DEGREES OF FREEDOM END EFFECTOR PLACES 8000 LB. ROBOTIC CANISTERS IN THE NATIONAL IGNITION FACILITY

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ABSTRACT

The National Ignition Facility (NIF), currently under design and construction at Lawrence Livermore National Laboratory, will be the world's largest laser when complete. The NIF will use about 8,000 large optics of 26 different types to focus up to 192 laser beams on a dime-size target. A system of auto-guided robotic vehicles transports opto-mechanical packages, called line replaceable units (LRUs), for installation and maintenance operations. Most LRUs are transported inside a portable clean room, or canister, containing robotic mechanisms that insert each LRU into its respective location in the laser. Together the LRU and canister can weigh up to 8000 lb. Due to precision-alignment requirements of the LRU and because the canister internal mechanisms operate in the canister reference frame, the canisters themselves must be precisely located relative to the laser support structure. In many instances precise location is obtained with the aid of precision canister locating points, called docking points, some of which are on the laser bay ceiling at 19 feet off the floor. The robotic vehicle transporting the LRU and canister is tasked with positioning these 8000 lb. canisters at 19-foot elevation with less than one inch offset error. The final positioning of the canister in six degrees of freedom is accomplished with an actively controlled three degree of freedom end effector coupled to a passive three degrees of freedom canister lift system.

1. Introduction

Large (6' x 5.5' x 10.5') bottom loading canisters provide the base platform from which robotic mechanisms operate to insert large opto-mechanical modules, called Line Replaceable Units (LRUs), into the National Ignition Facility (NIF) laser from underneath the laser enclosure. Precision placement and alignment requirements for the LRUs in the laser require that the canister be accurately positioned relative to the laser support structure / enclosure. Auto-guided vehicles (shown in Figure 1), called transporters, which are part of the Laser Bay Transport System (LBTS), transport these canisters throughout the NIF laser bay, then lift and position them at 528 separate parking locations. Over one third of the parking locations require that the canister be positioned and aligned within a one inch capture zone of a kinematic mount on a 19' high ceiling. To accomplish this, the transporters are equipped with a precision guidance system that accurately positions and orients the vehicle, a vehicle tip/tilt system, a lift system and a load fine positioning system. Together these systems place the canister kinematic mounts within one inch of their capture zone: three conical receptacles inset into the ceiling. Final sub-millimeter positioning of the canister on the ceiling is accomplished by use of four air-driven lift legs on the canister. When the lift legs are deployed the transporter fine positioning system is placed into a passive, back-drive mode. Final precision placement is then obtained by the mating engagement of the canister docking mounts with the laser support structure docking receptacles.

We describe how the combined system of transporter and canister successively achieves finer positioning of the canister relative to the laser support structure, the sequence in which the various components are exercised and the feedback sensor systems and control laws used.

2. Four successive levels of positioning control

The transporters in the LBTS are guided by a combination of inertial and laser scanner reflective feedback. Guide paths are laid out in the on-board computer memory with aid of a CAD representation of the NIF laser bay. On this CAD map are located the parking positions for canister docking, the building walls and other obstructions and the position of retro-reflective targets mounted at 8' elevation throughout the laser bay. The retro-reflective targets are places such that the on-board laser scanner/sensor can see four or more targets at any point along the travel path. The pulsed laser scanner/sensor uses both angle to reflective target and time of flight to triangulate its position in the laser bay. A Kalman filter combines the laser scanner triangulated position with inertial guidance data obtained from an on-board rate gyro and wheel encoders to determine the transporters position along the guide path within 1 inch. When the transporter approaches a parking location at which a canister will be docked, the transporter slows down to obtain a positioning accuracy of _ inch and a vehicle orientation accuracy of _ degree. This is the first level of position control for the canister.

Since the top of the canister must be raised to 19' off the floor, the level of the lift platform and the transporter has a large influence on the lateral position of the canister top. Therefore the second system for position control of the canister involves three leveling jacks at the base of the transporter. These jacks can lift the entire transporter off the ground if needed, but typically only operate within a range of one inch to level the canister lift platform with respect to gravity to an accuracy of 0.01 degree.

Once the transporter is leveled, the lift operates to raise the canister's top within 8 inches of the 19'-high laser bay ceiling. At this distance, a canister-mounted camera, looking upwards, can focus on a reference mark inscribed into the bottom of the LRU cover plate located within the docking plate which makes up the bottom portion of the NIF laser enclosure: the ceiling at that docking location. The image of the reference mark is acquired and processed to determine its offset in the camera's frame of reference. This offset is then fed to the transporter's Fine Positioning System (FPS) which constitutes the third level of positioning control. The FPS rotates the load platform about an axis on the load-side of the lift mast, translates the platform laterally in z then moves the canister longitudinally on the lift platform along x until the offset from the reference mark, as seen by the camera, is zero. In the laser bay the NIF coordinate axes are arranged such that $+z$ points in the direction of laser beam travel, $+y$ is vertically up, and $+x$ forms the third vector of an orthogonal triad. Offsets from the reference point and control motion directions are represented in the NIF coordinate frame. The range of the FPS includes ±2-inch travel in x or z and ±2 degrees of rotation about y. This range is sufficient, and the accuracy of motion is adequate to bring the three docking pins on the top of the canister within the one-inch capture range of their mating receptacles in the bottom of the laser enclosure. At this point the transporter lift, slowly raises the canister until a proximity switch on top of the canister activates. At this point the top of the canister is within 2 inches of the ceiling and another reading of the offset from the reference point is provided by the vision feedback system. The FPS does its final adjustment based on the offset information obtained by the vision system by rotating the load platform followed by laterally translating the load platform, then longitudinally displacing the canister on the load platform. Once the offset from the reference has been driven to zero, the canister is raised to begin engagement of the docking pins until feedback from the proximity sensor indicates that the tops of the docking pins are above the conical receptacles entrance-plane.

The fourth and final level of positioning control is done with the docking pins entirely within the 1-inch lateral and 7/8-inch vertical travel range of the conical docking receptacles. The transporter's lift platform is locked from further motion. The FPS system is put into passive mode by allowing the motors to be back-driven. The canister air legs are activated to lift and tip/tilt the canister until each of the three docking pins is fully seated within its corresponding docking receptacle. During this final stage the canister can translate fractions of an inch and rotate about the vertical by fractions of a degree as needed through the back-driven FPS. Once the canister is fully seated the location accuracy of the canister top is within tenths of an inch (a few millimeters) relative to the laser support structure.

3. A camera vision feedback system enables the third level of positioning control

During the third level of positioning control, when the transporter FPS system is active, the control signal is obtained from the observed offset of a reference mark inscribed into the LRU cover plate inside the docking plate, which is the bottom of the laser enclosure at the docking port. The offset of the reference mark is referred back to the transporter coordinate frame as shown in Figure 2.

Since the first operation of level-three positioning is the rotation of the lift platform by the transporter, the angle offset _ is zeroed out. This operation causes the X_C and X_T axes to align with the orientation sense in the reference mark. In the rotated coordinate frame, labeled X_{1T}, the new offset of the reference mark center from the transporter frame origin is D_1 where

$$\vec{D}_1 = R_y(\theta)\vec{D} = R_y(\theta)\left(\vec{L} + \vec{D}_C\right). \tag{1}$$

After the rotation the canister is translated laterally, then longitudinally until the offset distance $\vec{D}_{C1}$, as seen in the camera, is zeroed out.

$$\vec{D}_{C1} = R_y(\theta)\vec{D} - \vec{L} = R_y(\theta)\left(\vec{L} + \vec{D}_C\right) - \vec{L} = \left(R_y(\theta) - 1\right)\vec{L} + R_y(\theta)\vec{D}_C \tag{2}$$

The lateral translation is along $\hat{z}_{1T}$ and the longitudinal translation is along $\hat{x}_{1T}$ by the amounts given in Equation (3).

$$\begin{aligned}\vec{D}_{C1} = &\left\{\left[(\cos(\theta) - 1)L_x - \sin(\theta)L_z\right] + \cos(\theta)D_{Cx} - \sin(\theta)D_{Cz}\right\}\hat{x}_{1T} + \\ &\left\{\left[(\cos(\theta) - 1)L_z + \sin(\theta)L_x\right] + \cos(\theta)D_{Cz} + \sin(\theta)D_{Cx}\right\}\hat{z}_{1T}\end{aligned} \tag{3}$$

This last expression can be simplified in operation by making use of the fact that the angle _ is small (less than 0.04 radians) and that the largest length is L_x, which is approximately 57" or 31.5" depending on the orientation of the canister on the load platform. All other lengths are on the order of 1". Making the small angle approximation for the sinusoids in Equation (3) thereby dropping terms of order $\frac{1}{2}\theta^2 L_x$ and terms of order $\theta\{L_z \text{ or } D_{Cz} \text{ or } D_{Cx}\}$ gives

$$\vec{D}_{C1} \cup D_{Cx}\hat{x}_{1T} + \left(D_{Cz} + \theta L_x\right)\hat{z}_{1T}\ . \tag{4}$$

Here the longitudinal translation is driven only by the longitudinal offset seen by the camera. The lateral translation is driven by a combination of the lateral offset seen in the camera and the prior angle of rotation times the known offset of the camera frame origin in the transporter frame. When applied in a sequence of two separate steps, as outlined in Section 1, this control law positions the canister to within fractions of an inch (a few millimeters) of its intended location.

4. Precise location within 10 mills

The final precision location is accomplished with the aid of three docking pins located on top of the canister. These docking pins slide into conical seats in the laser enclosure docking plate. The amount of room for the docking pins to seat is ±1 inch laterally while each pin inserts a distance of 7/8 inch into its seat. Together with radially directed slots in which the docking pins can slide, the pins and conical seats constitute a kinematic mount for the canister on the ceiling. With the canister air legs and the lateral degrees of freedom provided by back-driving the FPS, the kinematics of this system are analogous to the canister being set into kinematic mounts on the floor. The canister air legs provide a constant force (similar to gravity) on the canister while the FPS provides for almost-free motion in the lateral directions.

Figure 3 shows the details of a single docking pin and conical seat. The lateral force moving the canister into its final position is developed at the pin/cone contact surface. This force must be large enough to overcome the friction at the pin/cone contact and the back-driving resistance of the FPS. Given that the top plate of the canister is nearly parallel to the laser-enclosure docking plane, simple two-dimensional geometric considerations give the available lateral force F_L as a fraction of the net available vertical force F_A applied by the air legs as:

$$F_L = \tfrac{1}{2}\left[\sin(\Omega) + \mu\Theta\left(F_A \cos(\Omega/2)\right)\left(\cos(\Omega)-1\right)\right]F_A \, . \tag{5}$$

Here Ω is the conical-seat cone angle, μ is the coefficient of friction and $\Theta(x)$ is the Heaviside unit step function: $\Theta(x \leq 0) = 0$, and $\Theta(x > 0) = 1$. With the coefficient of friction [1] for lubricated, hard steel on hard steel of 0.23, we obtain that 28% of the applied axial force is available to move the canister laterally until the three docking pins seat.

Together, the four canister air legs can develop up to 2000 lb. of vertical, axial force above the weight of the canister, thereby applying up to 560 lb. of lateral force on the canister. The worst-case FPS back-drive frictional resistance arises in moving the load platform laterally and rotating the load platform about its hinge. At full weight, this requires a force of 150 lb. The longitudinal back-drive force is small: about 42 lb., but a sagging of the forks of 0.2° can add an additional resistance of 30 lb. for a net resistance of 72 lb. The total, horizontal resistive force is the vector sum of the lateral and longitudinal resistances: 166 lb. Therefore, approximately 390 lb. of force is available to move the canister docking pins into their seated positions.

Tight machining tolerances are held on the conical seats and docking pins so that, once seated, the docking pins locate the center of the canister top plate within 10 mills of its intended location.

5. Conclusion

We have demonstrated how the LBTS achieves its positioning accuracy when placing 8000 lb. bottom-loading canisters at their docking sites in the NIF laser. We also described the mechanisms that operate to successively refine the canister's six-degree of freedom relative position with respect to the laser enclosure until the canister is docked within tens of mills.

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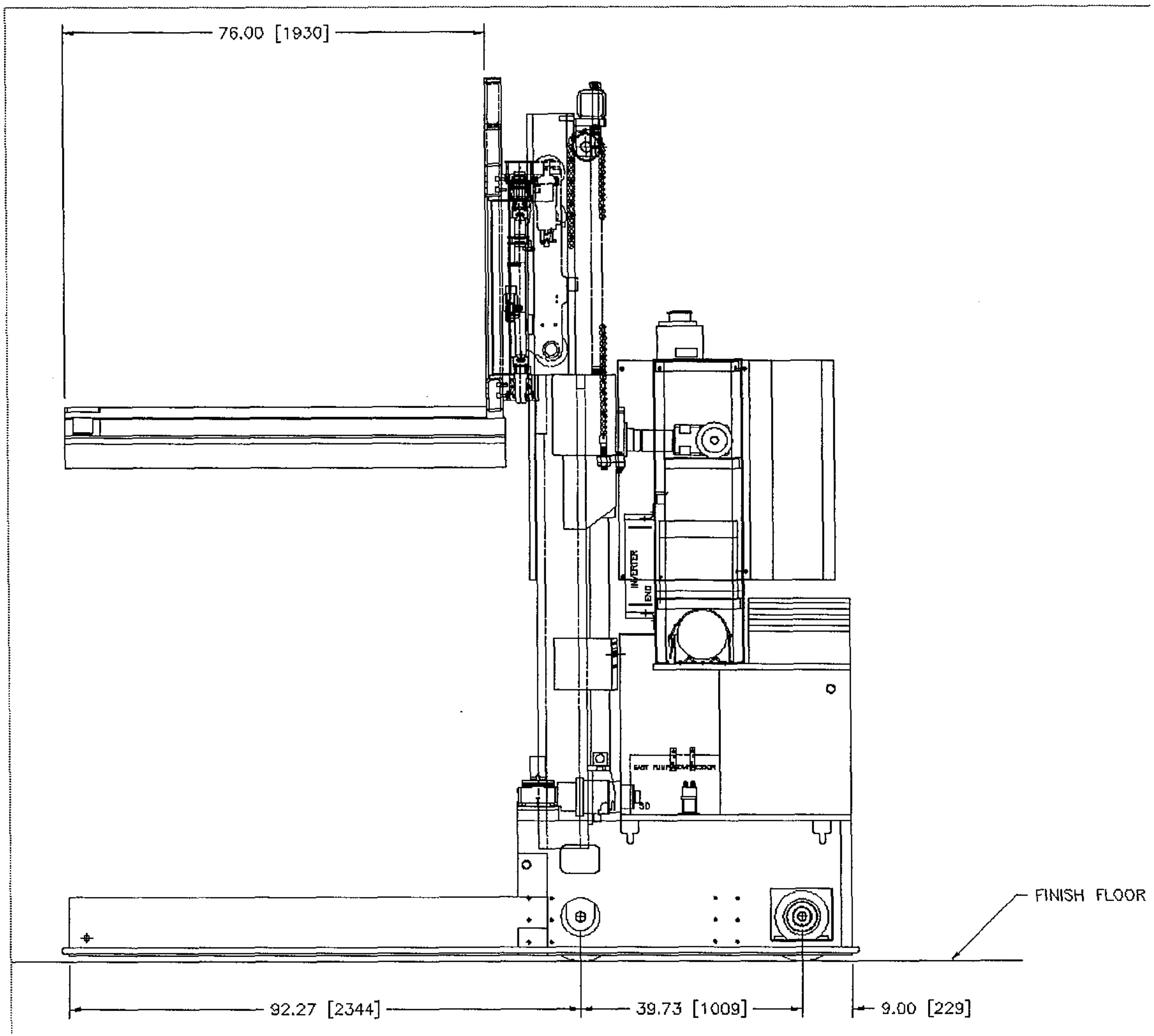

Figure 1. Side view of one transporter in the Laser Bay Transport System. The load platform, consisting of two forks and the Fine Positioning System (FPS), is shown raised near 80% of its full height. The laser guidance scanner head is seen on top of the transporter body, near the center of the picture. The FPS rotates the load platform ±2° about a hinge axis on the load side of the lift-mast. It translates the platform laterally ±2" (perpendicular to the plane of the paper) and translates the load longitudinally ±2" (along the length of the forks).

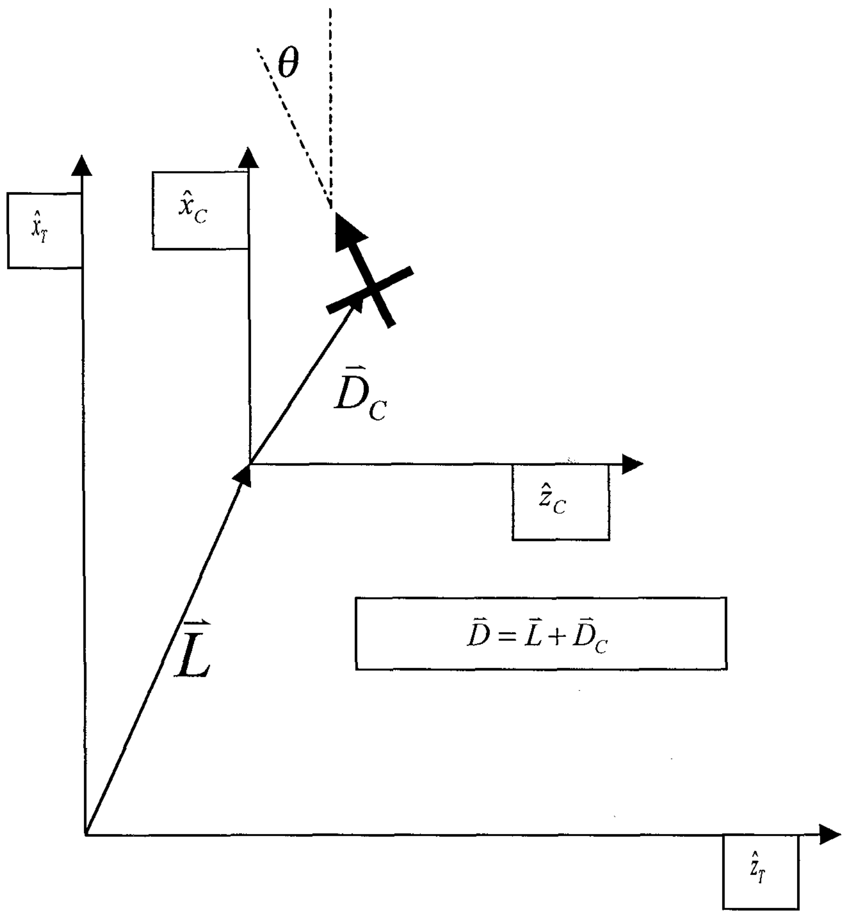

Figure 2. Representation of Transporter X_T and Camera X_C coordinate frames and the canister placement/alignment reference mark as seen in the camera. The origin of the transporter reference frame is at the transporter load platform rotation axis. The origin of the camera reference frame is defined in the camera CCD. The camera and transporter frame axes are collinear. $\vec{L}$ is the offset vector of the camera from the transporter origin and $\vec{D}_C$ is the offset vector of the reference from the camera origin. θ is the misalignment of the canister from its intended docking orientation.

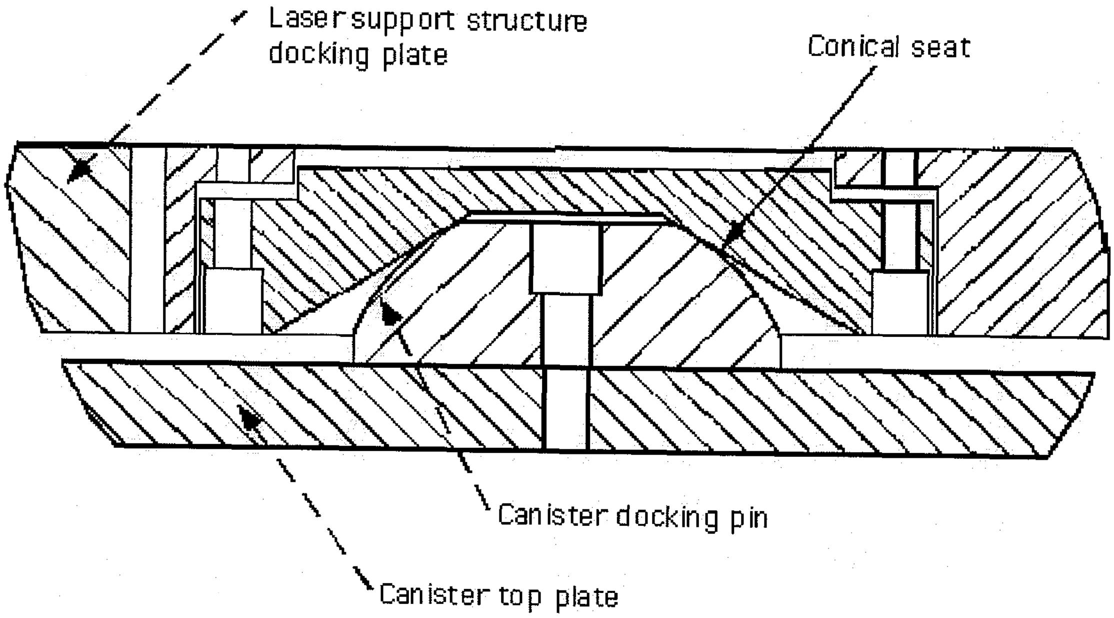

Figure 3. Sketch of one of the canister docking pins and its mating conical seat in the laser enclosure. The cone angle is 116 degrees and the opening of the cone at the ceiling is 2 inches in diameter. To achieve a kinematic constraint the docking pins are set into slides that ride in radial grooves. The combination of three of these is approximately equivalent to a ball in v-groove kinematic mount.